Science & Technology Facilities Council
Daresbury Laboratory

A Staged, Multi-User X-Ray Free Electron Laser & Nuclear Physics Facility based on a Multi-Pass Recirculating Superconducting CW Linac

AND

The Path to UK-XFEL by means of an Industrial Accelerator for Nuclear Photonics & Semiconductor Lithography

Peter Williams
ASTeC, Daresbury Laboratory & Cockcroft Institute, UK

Workshop on Energy Recovery Linacs (ERL2019)

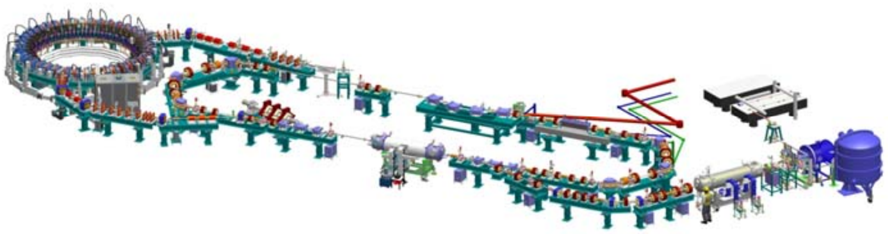
16th September 2019

The Cockcroft Institute
of Accelerator Science and Technology

bERLin 2019

A UK-XFEL? What to aim for?

- UK now has a long and distinguished record of failed XFEL projects! 4GLS (2006), NLS (2010) – although the test facilities they spawned have been successful in their own right: **ALICE** ERL-FEL (2006 – 2016), CLARA (2014 - …)



- The 2016 STFC FEL Strategic Review:
  - Committed UK to membership of EU-XFEL and…
  - Stated UK should consider constructing a dedicated facility in the 2020s – established an R&D effort
  - The first major decision that must be made in defining a UK-XFEL is whether to build based primarily on a **warm, pulsed normal-conducting linac (NC)** or a **cold, continuous-wave superconducting linac (SC)***
  - Executive summary: *"In order to address the majority of the key science challenges, a UK facility would need to deliver **hard X-rays**. To further broaden the range of science which could be tackled, the ideal machine would also have a **high repetition rate**. However, this is likely to be unaffordable as a national facility…."*
  - Hence the dilemma: **NC is a cost-driven limited capability option, SC is a full capability, expensive option**

A UK-XFEL? What to aim for?

- 2019: UK Government launches another UK-XFEL science case consultation
  - Remit to be **ambitious** and **creative**

UK XFEL Science Case Exercise

Jon Marangos

Blackett Extreme Light Consortium (XLC)

Imperial College, London

in partnership with STFC

Royal Society July 16th 2019

A UK-XFEL? What to aim for?

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UK XFEL Science Case Exercise

This is a Long Range Science Planning Exercise

- It will deliver science for the late 2020's, 2030's, 40's & 50's
- It had better be a cutting edge machine at first light or it will soon be obsolete
- We should think long range and about things that NO current or planned XFELs can do
- We need to take a wide view of where there will be science impact
- We need to consider the full range of advanced industries in the UK that this facility will serve
- Need to see it as an important part of the international network of Light Source provision (not necessarily doing everything – but certainly doing some things better than anywhere else)

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What capability is the science likely to demand?

- **Soft to hard x-ray (0.1 – 10 keV), (maybe harder, maybe VUV)**
- **Short X-ray pulse available (< 0.5 fs)**
- **Two pulse/two colour with delays over sub-fs to ns**
- **Synchronised or tagged to lasers to high precision (< 5 fs)**
- **High spectral brightness/narrow-bandwidth available (< 50 meV)**
- **High rep-rate is mandatory for much advanced science (chemical, quantum materials, rare events …) (> 1 kHz maybe > 1 MHz)**
- **High photon pulse energy (~ 10^{12} photons/pulse, maybe not at full rep-rate)**
- **Polarisation control (Linear, circular, OAM)**
- ……….

The science case will help define the scientific and therefore the facility technical priorities

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- **High rep-rate is mandator quantum materials, rare**
- **High photon pulse energy rate)**
- **Polarisation control (Line**
- **...........**

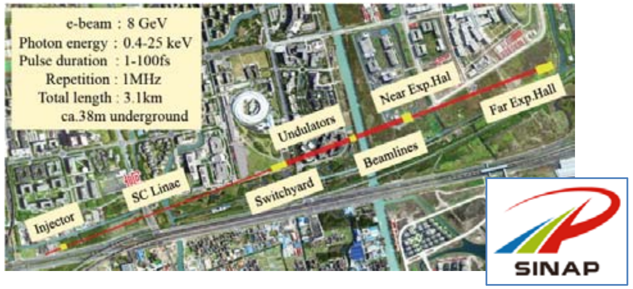
The science case will help define the scientific and therefore the facility technical priorities

Advanced concepts include .....

- Attosecond modes (XLEAP, Attosecond pulse trains,....)
- Increased spectral brightness (e.g. RAFEL or X-ray oscillator)
- Increasing rep-rate (non-SC limits ~ 1 kHz, new concepts ~10 MHz)
- Super-radiance schemes to increase power and shorten pulse
- X-ray seeding (e.g. using an "Arizona" type device to seed with super-radiant incoherent Compton X-rays)
- Increased photon energy via non-conventional electron energy boost:
- Multi-pass linac
- PWFA

Already we have seen enormous advances in capability over last 10 years. For example in reaching the sub-femtosecond regime.....

So… You Want to Build A CW MHz Repetition Rate Hard X-Ray FEL?



Can we decrease the cost?

Can we increase the science it buys?

Can we do both simultaneously? …

Why do we build one full energy single-pass linac? Are we as a community being too conservative and inefficient?

What additional capability could we enable with a more radical approach?

We should consider recirculation… and energy recovery

… and up to what energy? … consider multi-frequency cascading?

In Addition to Cost Mitigation, Recirculation Opens the Door to Extend Science Reach through Energy Recovery

TWO stages of accelerator development, staging the capability, and assessing the cost-saving potential as a function of N = number of accelerating linac passes

1. N-Pass*
2. N-Pass with Energy Recovery

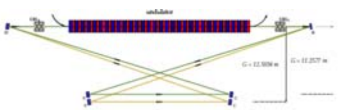
*** Where N = 1 (full energy single pass SC linac = no recirculation), 2, 3, 4 (recirculating SC linac)**

Additional capability of an ERL stems from the **high average virtual beam power** available, we should **expect future user demand** for such capability for:

1. Enabling **transform-limited pulses at ~10 keV** through deployment of XFELO & RAFEL – Requires Multi-MHz
2. Industrial & scientific uses for longer wavelength high average power sources enabled by ease of access to lower energy recirculation passes: **100 eV – 1 keV**
3. Harmonics of fundamental 10 keV MHz sources due to the high spectral brightness wrt SASE – **100 – 1000 keV**
4. Inverse Compton Scattering (ICS) **narrowband (10^{-4} – 10^{-5}) gamma sources** in two regimes – ~10 MeV & multi-GeV
5. Internal target electron beam experiments – e.g. precision standard model measurements, dark matter searches, medical isotope production

An FELO for hard X-Rays; XFELO

- XFELO was first proposed by R. Collela and A. Luccio at 1983 BNL workshop by using Bragg reflectors as high reflectivity normal incidence mirrors
  - The same WS where BNP proposed SASE
  - Taking into account of the advances in accelerator (ERL)and x-ray optics, it was "resurrected" in 2008 by KJK, Y. Shvyd'ko, and S. Reiche

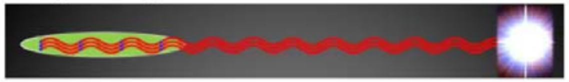


- Tuning is possible with the four-crystal, zigzag cavity
  - R. M.J. Cotterill (1968, ANL); KJK and Y. Shvyd'ko (2009)
- Electron beam with a constant, ~ MHz rep rate will be ideal

An X-Ray FEL Oscillator is fully coherent and stable

- Full transverse and longitudinal coherence
- Transform limited BW: $\Delta\hbar\omega =$ (3-10) meV for (0.3-1) ps pulse length
- 10^8-10^9 γ's /pulse, or 10^{14}-10^{15} γ's /second
- Complete polarization control with crossed U

→100-fold higher spectral flux, 10,000-fold higher brightness than USR



Up to 1 keV sources could be RAFEL (high gain / low Q): E.g. Cavity using multilayer mirrors with low reflectivity: undulator length should be ~half the length of a SASE undulator so cavity perimeter ~ 60m, so round trip frequency = **5 MHz**

Such oscillators benefit greatly from **MULTI-MHz repetition rate** bunches – i.e. 1 MHz should be seen as a lower limit

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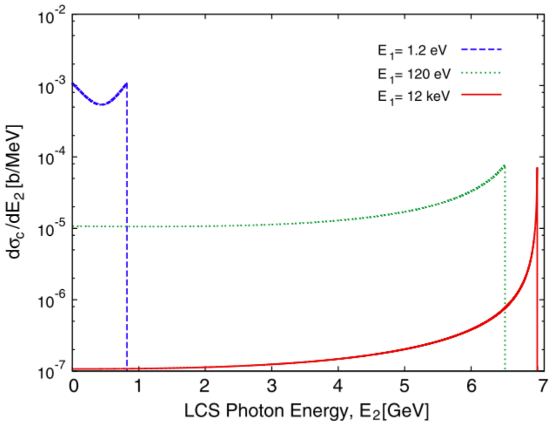
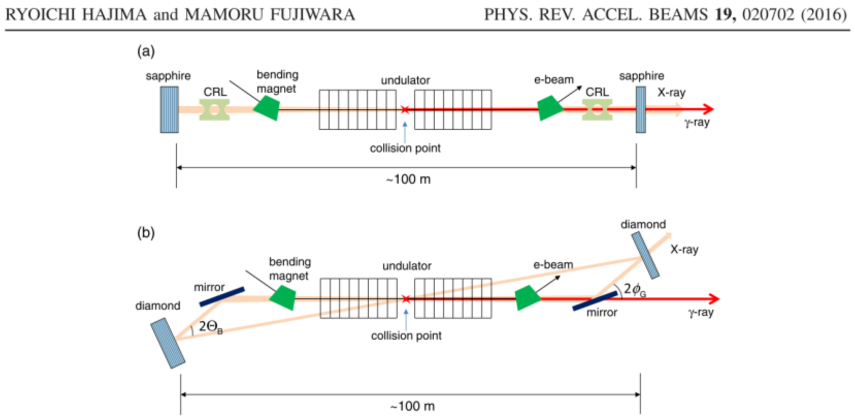
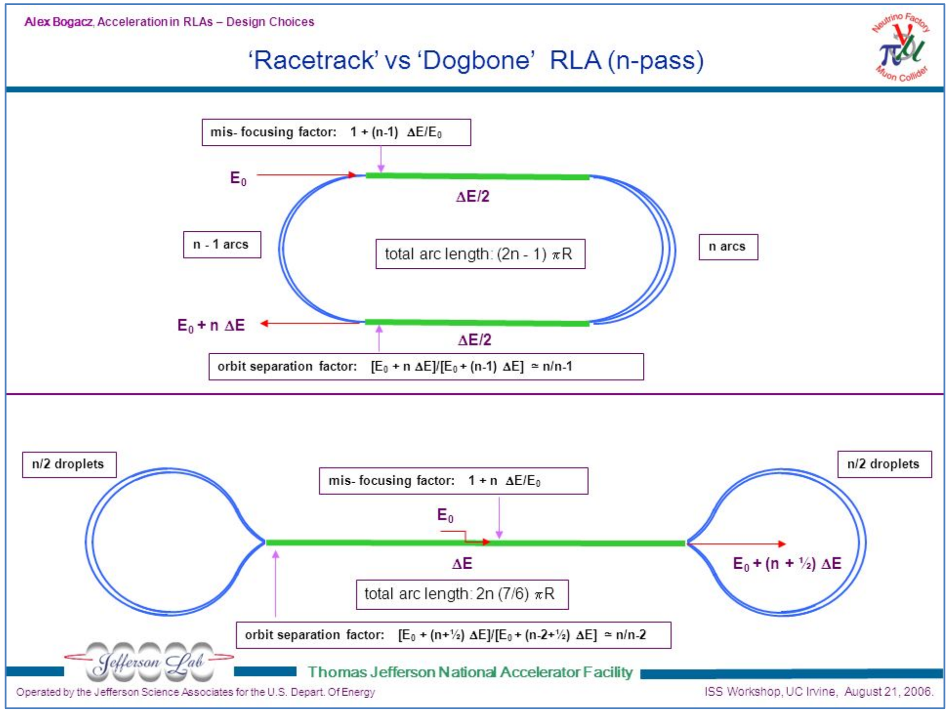




Multi-GeV ICS: narrowband would enable precise hadron spectroscopy through electron recoil-dominated ICS self-interaction in an XFELO / RAFEL.

In a Multi-Pass ERL, One Has a Choice of Topology

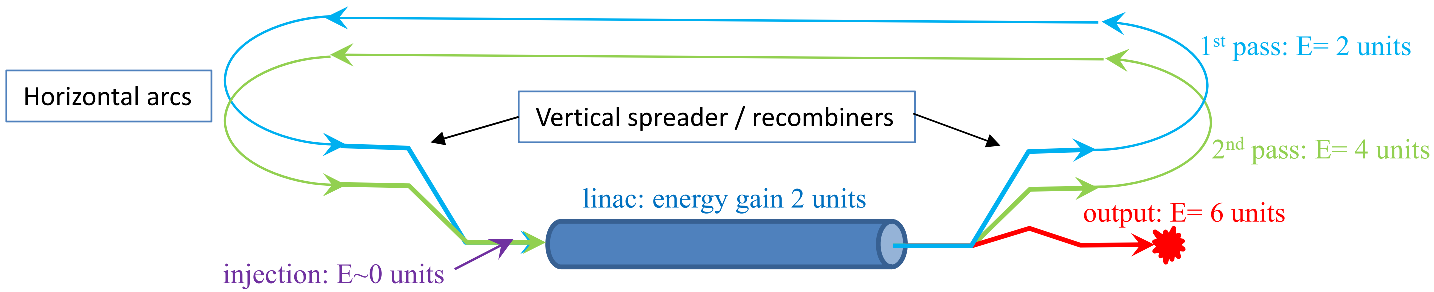


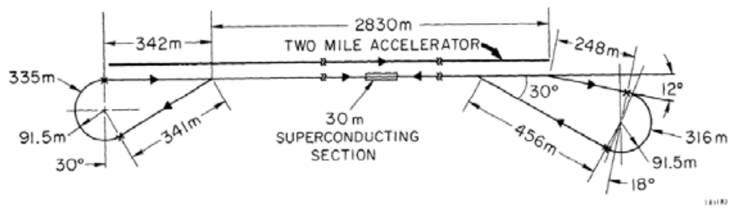
Option 1: "Dogbone" Types:

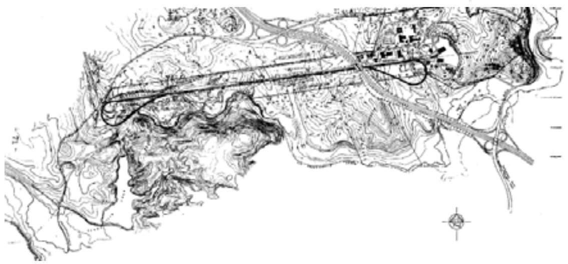
- These have been extensively considered by Alex Bogacz (JLab) in context of LHeC, Neutrino Factory and Muon Collider
- They are advantageous in the 100's GeV, low current regime as they are more efficient in utilising RF
- We **reject** these in the context of few GeV scale with 10's mA current as there is no way to implement ion clearing gaps in such configurations
- Push-pull configurations not appropriate for staged approach at GeV scales

In a Multi-Pass ERL, One Has a Choice of Topology

Option 2: Monolith: One linac with long bypasses (3-pass shown here)



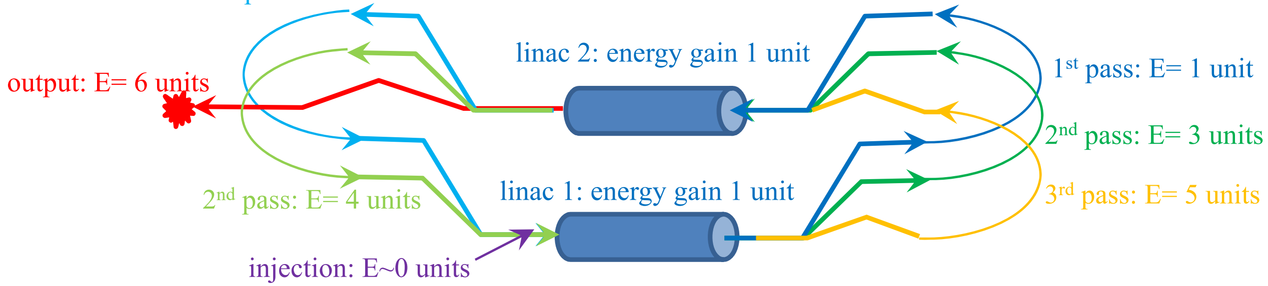




- First considered originally for SLC in 1968! (before discovery of RF pulse compression) W. B. Herrmannsfeldt et. al. SLAC-TN-71-004, SLAC-R-139
- Also used in UK NLS recirculating design
- Cryogenically simple, however tunnel packing fraction is low (or additional arc bending = no cost advantage over split types, so **reject**

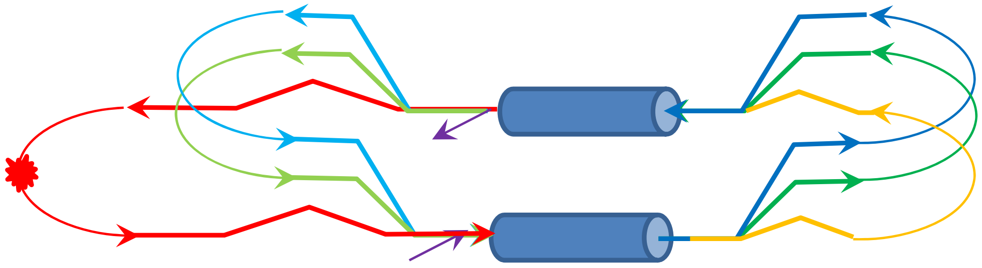
In a Multi-Pass ERL, One Has a Choice of Topology

Option 3: Symmetrically bisected: Split linac into two identical half-linacs on opposite sides of a racetrack



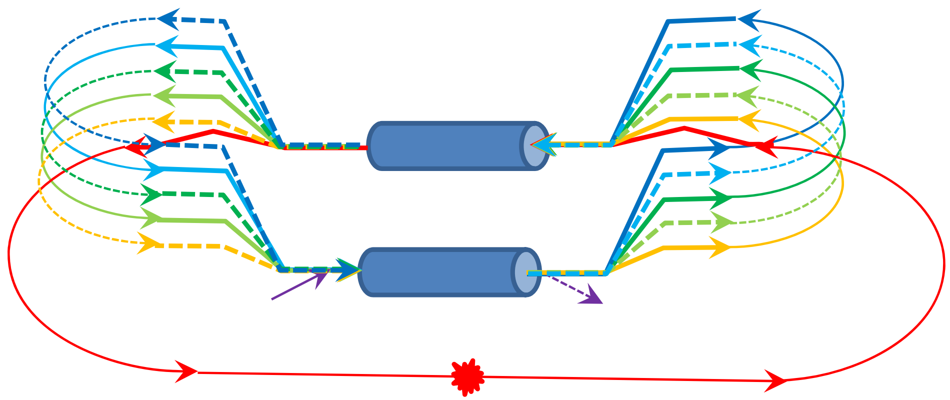
- CEBAF-like, also used in design for PERLE / LHeC
- With respect to the monolith, this increases the packing fraction of linac to tunnel
- When we implement energy recovery, we are faced with a choice…

In a Multi-Pass ERL, One Has a Choice of Topology



Option 3a: **Re-inject the spent beam into L1 = Common Transport**

- Other than re-injection this involves **no additional beamlines**
- The recirculation transport **necessarily** carries both accelerated and recovered beams simultaneously as their energies are very similar (true even when lasing / interaction and SR losses included). Therefore there is **no independent control of optics and longitudinal phase space** on deceleration
- A lesser design complication is that the east and west **splitter / recombiners are optically different** (energy ratios 1:3:5 and 2:4:6 respectively)

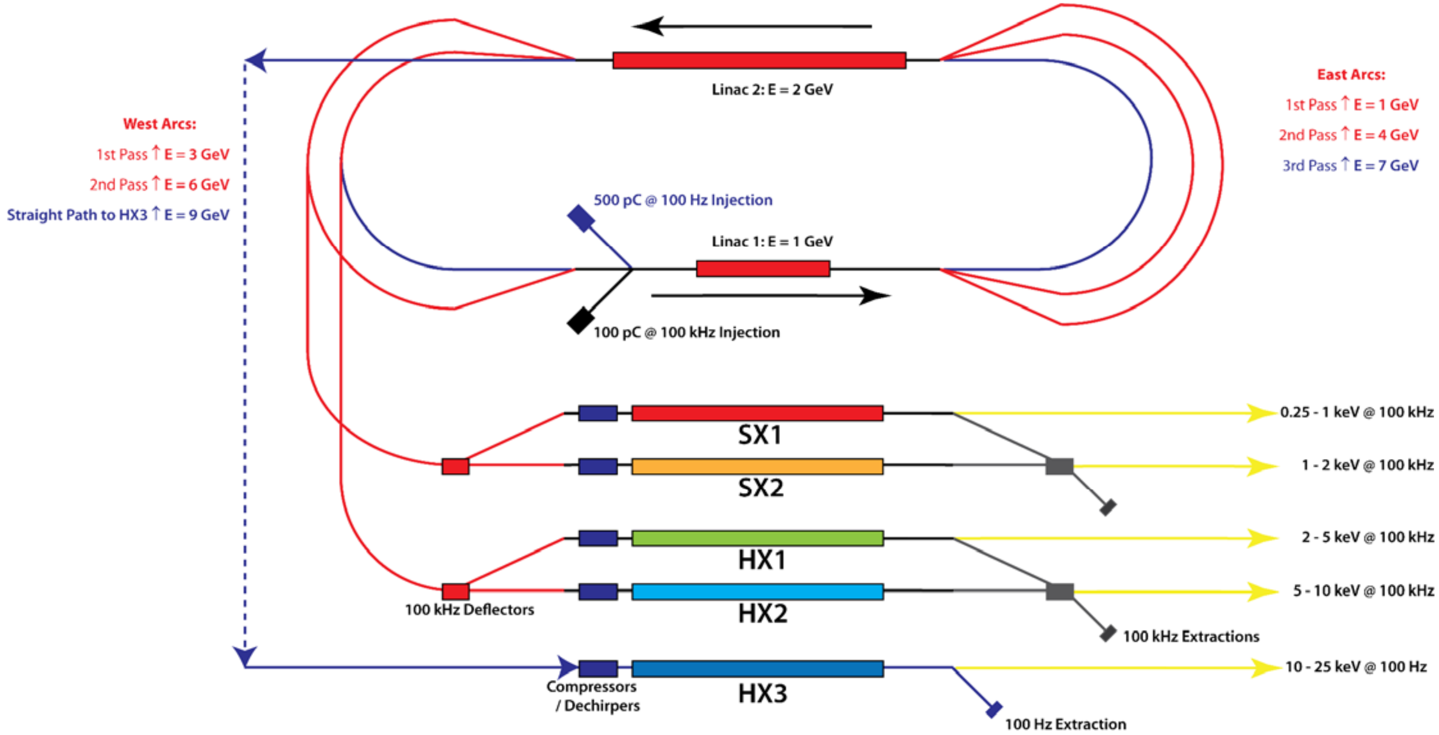


Option 3b: **Re-inject the spent beam into L2 = Separate Transport**

- The transport now carries both accelerated and recovered beams separately as their energies are distinct. This enables **individual pass-to-pass optics and longitudinal phase space control**
- The east and west **splitter / recombiners are now identical**
- In both cases L1 has a large **mismatch of focusing strength to beam energy** – limiting the focusing at the top energy – even with a "graded gradient" technique. Beam envelops thus scale as (linac length)^2 = errors! – BUT can mitigate this with **asymmetric linacs** or by **moving inj / ext part-way through L1** if needed

Strawman UK-XFEL Stage 1 based on Multi-Pass Recirculating Linac

- UK user consultations indicate the demand for MHz comes first at EUV to soft X-ray photon energies (100 eV – 10 keV) …
- This is driven by time resolved studies in biological systems in addition to raw average power needed in industrial applications
- … and the hard X-ray demand is in kHz but with higher pulse energy
- Motivates two injectors, and fast distribution to suite of FELs at of progressively higher photon energy and progressively lower repetition rate



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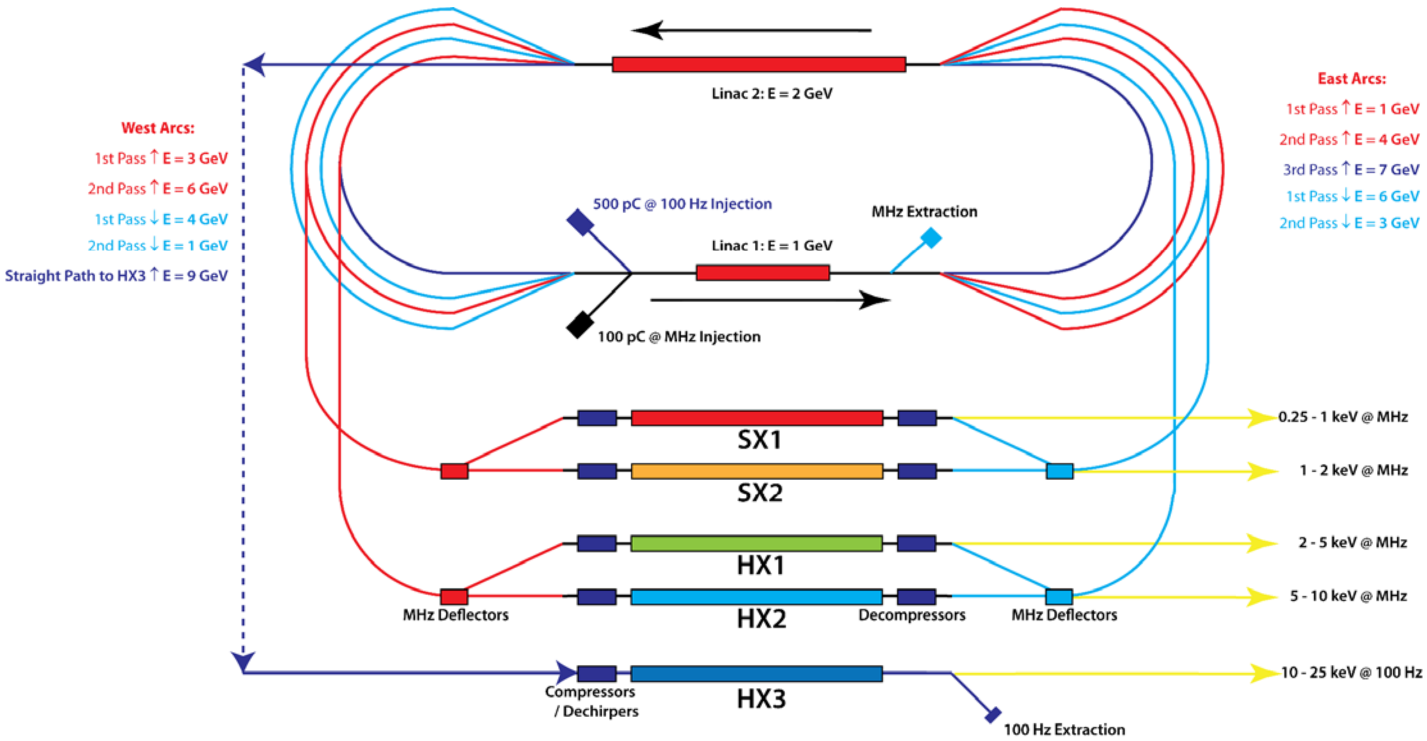
Strawman UK-XFEL Stage 2 based on Multi-Pass Energy Recovery Linac

- UK user consultations indicate the demand for MHz comes first at EUV to soft X-ray photon energies (100 eV – 10 keV) …
- This is driven by time resolved studies in biological systems in addition to raw average power needed in industrial applications
- … and the hard X-ray demand is in kHz but with higher pulse energy
- Motivates two injectors, and fast distribution to suite of FELs at of progressively higher photon energy and progressively lower repetition rate
- Upgrade to energy recovery enables Multi-MHz XFELO / RAFEL
- Perhaps replacing final pass with additional NC higher frequency linac – a hybrid SC / NC machine?



Set the Arc Size By Specifying Tolerable Slice Energy Spread AND Peak Current

- ISR usually considered in terms of quantum excitation of energy spread that leaks via dispersion into slice emittance growth, relevant formulae derivation from Matthew Sands (SLAC-121)

$$\sigma_E^2 = 1.18\times10^{-33}\ \mathrm{GeV}^2\ \mathrm{m}^2\,\frac{\gamma^7}{\rho^2} \qquad \Delta\varepsilon = 7.19\pi\times10^{-28}\ \mathrm{m}^2\ \mathrm{rad}\,\frac{\gamma^5}{\rho^2}\langle H\rangle$$

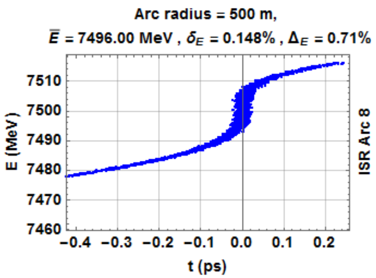
Where H is the usual term in the 5th radiation integral – i.e. dispersion dominated

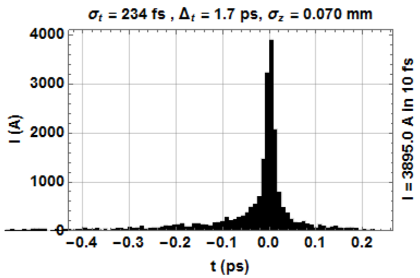
- In a ~10 GeV scale recirculated XFEL it turns out that the **longitudinal emittance degradation** is the limiting factor – i.e. we are concerned with the slice energy spread increase itself. Transversely we remain source dominated and can mitigate ISR emittance growth with isochronous, locally-symmetric arcs, C.-Y. Tsai et. al. [Phys. Rev. Accel. Beams 20, 024401]
- We recast Sands formula to see the relevant scaling: arc radius required to avoid growth to a specified relative slice energy spread

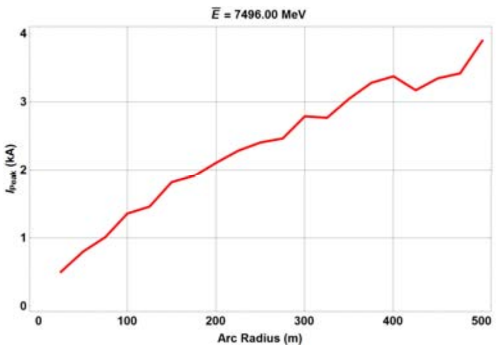
$$\rho = 6.7253\times10^{-14}\mathrm{m}\,\frac{\gamma^{2.5}}{(\sigma_E/E)}$$

For a fixed relative energy spread growth the arc radius scales as **energy to the power 2.5**

- In addition, through longitudinal phase space shearing used to compress the bunch this translates directly to **a limit on the peak current achievable** (exaggerate below by standing the bunch up in LPS and progressively reducing arc radii)



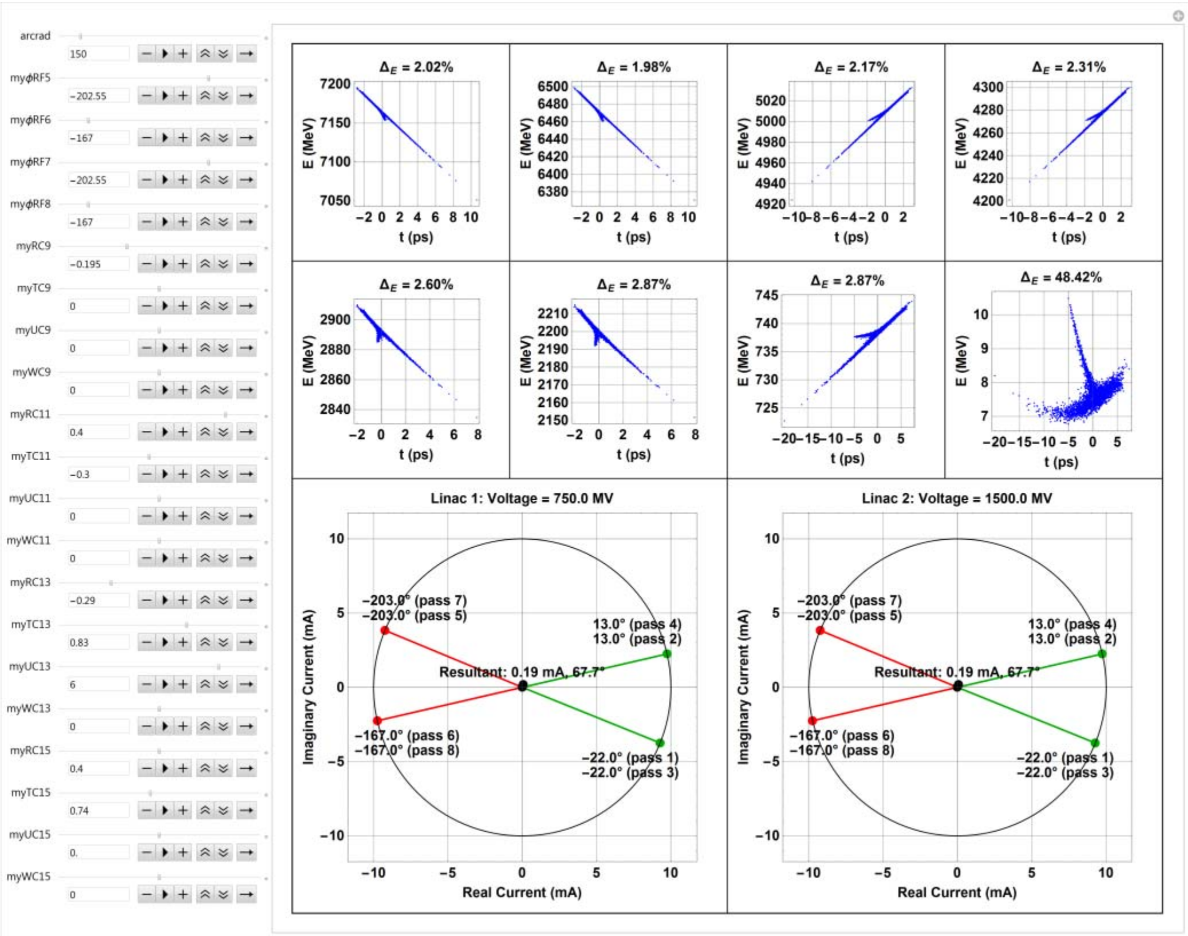




For this example **considering only the peak current** we should pick arc radius of 150 m to ensure ISR limit lies above 1.5 kA

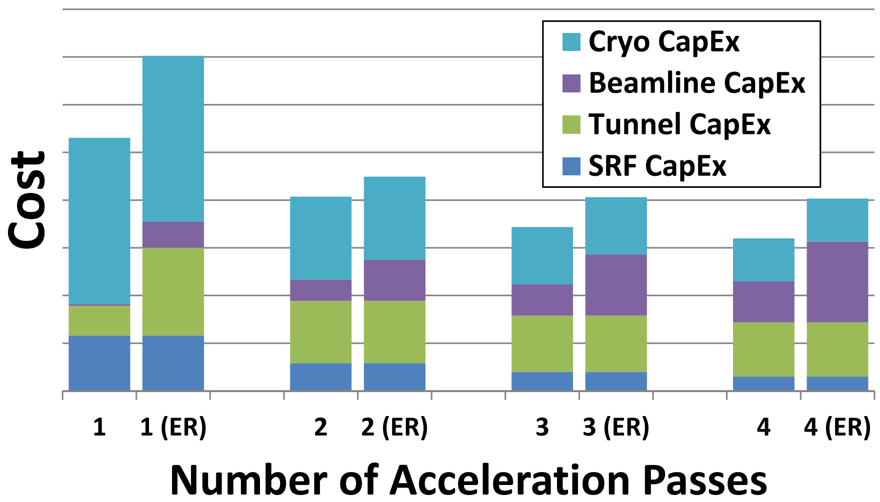
(c.f. LCLS SASE 10 keV peak current of 2 kA for 200 pC)

Successfully Recovering the Spent Bunch in a Compressive Multi-Pass ERL



- For > 1 MHz rep rates we must ensure full energy recovery, this requires self-consistent longitudinal phase space match with RF load balancing, accelerating bunch compression and decelerating bunch decompression (and energy spread compression)
- This match must also account for bunch disruption by FEL lasing (or internal target interaction) and ISR losses
- Global optimization of linear and higher order longitudinal transport terms in the arcs, together with pass-to-pass off crest phase achieves this (here we show a 4-pass implementation as example)
- Developing semi-analytic method to explore solution space, rather than trial-and-error – seem to be domains of solutions with qualitatively different characteristics – **See Poster: "Semianalytic Longitudinal Phase Space Solutions for Multipass Energy Recovery Linacs " Gus Perez-Segurana, PW**

Strawman UK-XFEL Recirculating Linac as a Cost Optimisation, Followed by Upgrade to Energy Recovery



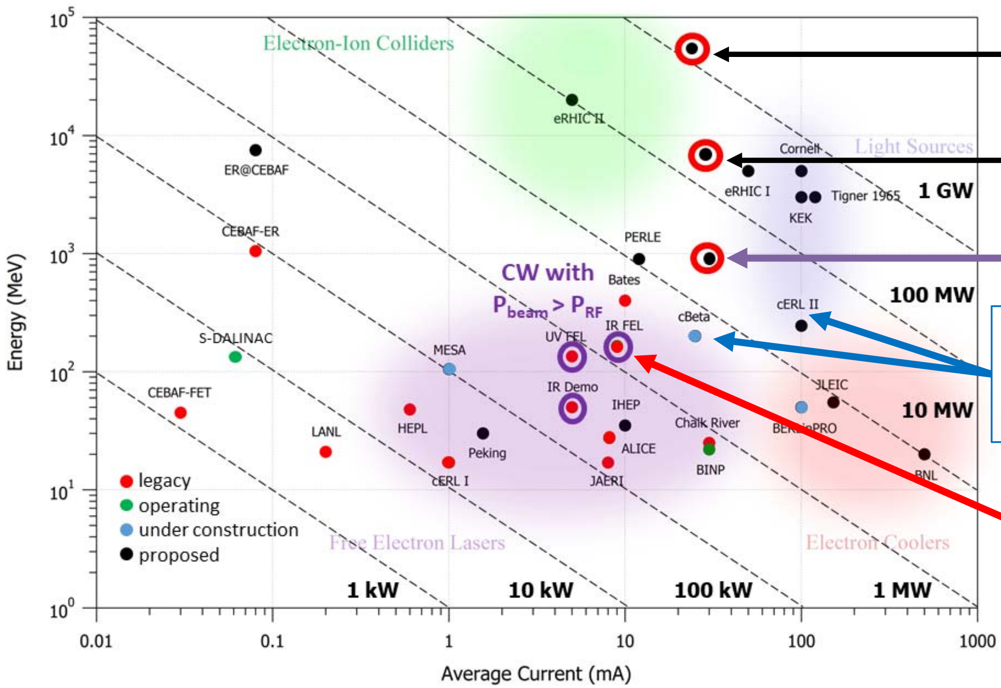
- E = 8 GeV, cost scaling as a function of N
- Max rep. rate of 1, 2, 3, 4 = **1 MHz**
- Max rep. rate of 1 (ER), 2(ER), 3 (ER), 4 (ER) **~ 100 MHz**

Indicative component contributions taken from previous project costings (JLAMP-X, NLS, LHeC)

- The “**1**” line is a straight linac, “**1 (ER)**” has a “long bypass”
- For all **N > 1**, fixed arc radii of 150 m, RF frequency 800 MHz, gradient 14 MV/m, switchyard 150 m, 50 m each for spreaders / recombiners / compressors
- We see a **~35% saving** for a 3-pass configuration as opposed to a 1-pass configuration
- It would then cost an additional **~10%** to implement Energy Recovery “3 (ER)”, enabling **additional capability** as linac would now support 100 MHz repetition rate without beam loading
- A 3-pass ER machine could thus be achieved with a cost **saving** over a 1-pass non-ER machine of **~25%**
- **This 8 GeV example is pushing at the upper limit: For E > 8 GeV the arcs become too expensive, for E < 8 GeV there is an even greater saving (for fixed ISR degradation**

However, Present State of the Art for ERLs Implies Too High Risk

- The relevant sanity check is the beam power circulating in the ERL
- To build a ERL UK-XFEL would be to go ~**two** orders of magnitude beyond that demonstrated
- To build an LHeC would be to go ~**three** orders of magnitude beyond that demonstrated
- Risk mitigate through the construction of a test facility!



Anticipate CBETA demo up to 40 mA CW, and cERL demo to 100 mA CW

Demonstrated ERL performance (JLab IR FEL upgrade)

Note: The risk resides in the beam power, NOT the recirculation transport

Cue … Long Meditation on Relative Motivations of Accelerator Facilities

Realisation that the unprecedented capability of providing electron beams of simultaneous high quality and high power at a lower energy e.g. 1 GeV has **been sought after** by parties external to the scientific community many times over recent years

Translation: Business development people keep saying "why can't you physicists provide what (insert company name here) want"?

Conclusion: **Propose An Industrial Applications Driven Machine**
(that is secondarily a test facility for a future UK-XFEL – or even the first stage of it)

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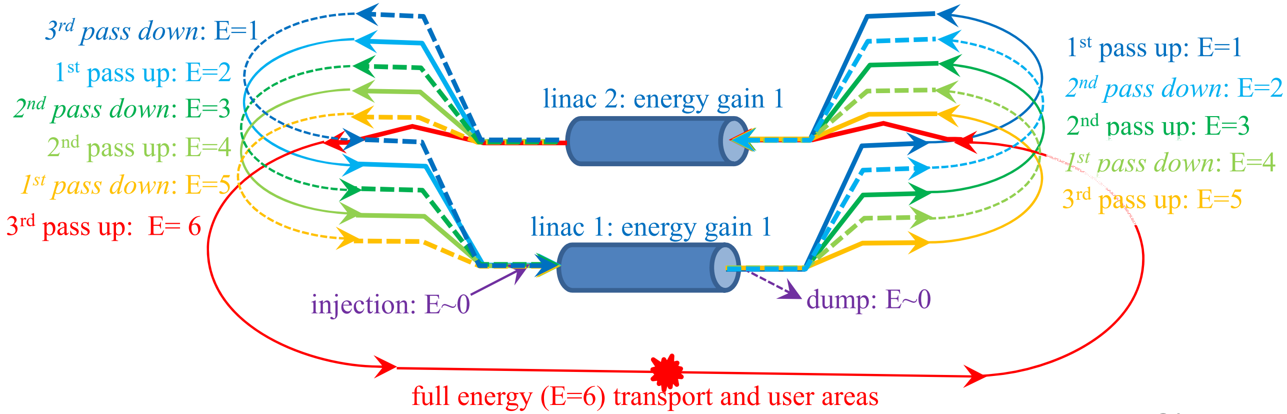
Daresbury Industrial Accelerator for Nuclear Applications (DIANA)

DIANA will be a multi-platform accelerator providing 1 GeV, high 6-d brightness, high average current electron beams for industrially-aligned and pure research. DIANA will drive (at least) three user facilities:

1. **A 10-100 kW average power EUV-FEL for semiconductor chip lithography industry research;**
2. **A high spectral energy density (10^7 photons / s . eV), narrowband (< 100 keV), 1-40 MeV inverse Compton scattering (ICS) gamma source for nuclear physics, nuclear decommissioning, security and medical isotope research;**
3. **An internal target experimental station for precision electroweak measurements and dark matter searches.**

Additionally, DIANA will serve as technology testbed for future proposed large scale facilities UK-XFEL and potentially also LHeC / FCC.

- Inspired by PERLE, but implements
  separate rather than common recovery transport
  ensuring independent pass-to-pass control of orbit, optics & longitudinal match
- Pair of 802 MHz SC cryomodules arranged in racetrack, each 170 MeV gain = 1020 MeV top energy. Two guns: one high current (~50 mA), one polarized
- A second stage could involve switching to common transport, implementing a “paperclip” topology for more user areas, and doubling energy, or current



Motivation for DIANA 10-100 kW average power EUV-FEL

- In order to keep pace with **Moore's Law** (doubling of CPU power every 18 months), industry moving from 193 nm light source to 13.5 nm – enables finer pattern etching on semiconductor wafers

- A major limitation is the power of the EUV light source → use an FEL?

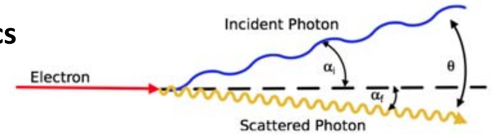
- Have received backing for DIANA from a large semiconductor lithography apparatus manufacturer, with whom Daresbury have an extensive relationship:

  - FEL is an interesting potential solution to generating multi-kW powers of EUV radiation
  - Energy recovery is a necessary condition to make such a light source economically viable
  - Valuable first step towards the industrial application of FEL's
  - Unique location for testing EUV optical components under intense illumination conditions

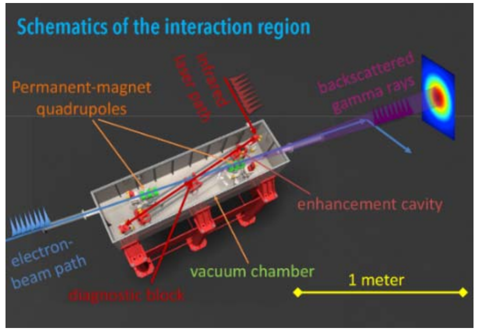
- A strong academic user case for such a FEL can also be made aimed at investigations in the water window

Motivation for DIANA 1-40 MeV ICS gamma source: Nuclear Photonics

- Aim: translate the “photonics” paradigm of atomic physics (1960’s onwards) to the nucleus = **Nuclear Photonics** = entirely new field of science due to new tool of **tune-able NARROWBAND gammas with high flux**

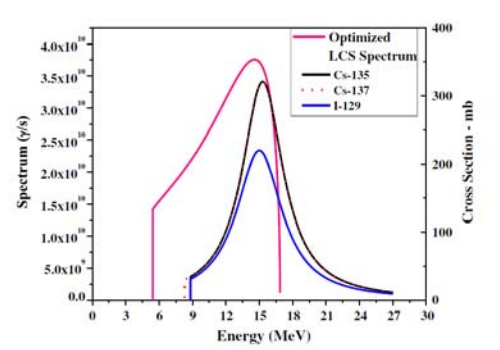


- This is motivation for ELI-NP Gamma Beam System in Romania, although the accelerator for ELI is pulsed C-band linac consideration was originally (~2010) given for ELI-NP to be based on an ERL



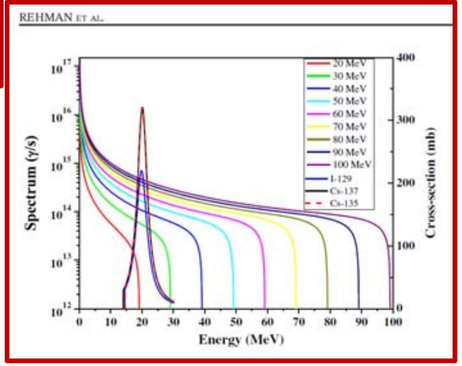
Fabry-Perot ICS IP for CW beam to perform demonstration on FAST@Fermilab (P. Piot)

- As an example of potential: broad photonuclear “dipole resonances” of nuclear structure are **not well matched** to energy spectrum of brem



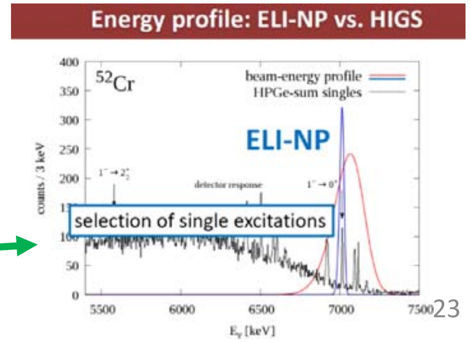
ICS spectrum compared to dipole resonances of I-129 and Cs-135/137

Brem spectra compared to dipole resonances of I-129 and Cs-135/137



- Raw, loosely collimated ICS gamma bandwidth **well matched** to dipole resonance, and flux enabled by ERL more than compensates for lower cross section of ICS vs brem = more efficient isotopic transmutation

- Narrow bandwidth further potentially allows selection of single nuclear excitations



DIANA ICS Gamma Source Conservative Parameters

Nd:YAG Laser Parameters	Value
Wavelength (nm)	1064
Repetition Rate (MHz)	100
Pulse Energy (μJ)	100
Average Stored Power in Cavity (kW)	10
Spot Size at IP (μm)	25
Stored Pulse Width (ps)	5.7
Field Strength of the Normalised Laser Vector Potential a_0	6.05×10^{-4}

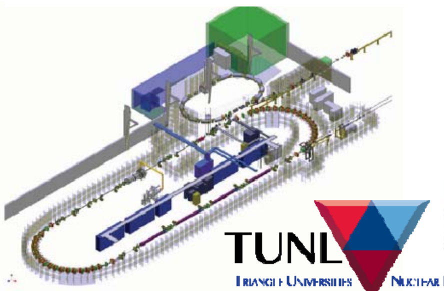
Already demonstrated laser parameters - taken from bowtie cavity used at KEK-cERL (T. Agaki) with now relatively standard 10 kW average power Nd:YAG laser

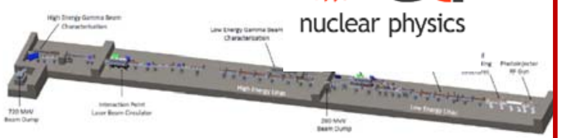
Beam Parameters	Value
Beam Energy (MeV)	340, 680, 1020
RF Frequency (MHz)	802
Repetition Rate (MHz)	100
Bunch Charge (pC)	100
Average Beam Current (mA)	10
Normalised transverse Emittance (mm mrad)	0.5
β function at the IP β^* (m)	0.5
Recoil Parameter X	0.006, 0.012, 0.018

Already demonstrated ERL accelerator parameters, but at higher energy

- **See poster "Tune-able, High-flux, Monoenergetic, 1-40 MeV Gamma Source Driven by Energy Recovery Linac for Nuclear Physics, Decommissioning, Security & Medical Isotopes" PW, Joe Crone, Hywel Owen (U. Manchester)**

Parameter	340 MeV	680 MeV	1020 MeV
γ-ray Peak Energy (MeV)	2.05	8.17	18.27
Flux per Shot (ph)	4076	4750	5027
Flux (ph/s)	4.08×10^{11}	4.75×10^{11}	5.03×10^{11}
Average Brilliance (ph/s mm^2-mrad^2 0.1% bw)	2.75×10^{13}	1.27×10^{14}	3.04×10^{14}
Peak Brilliance (ph/s mm^2-mrad^2 0.1% bw)	4.79×10^{16}	2.24×10^{17}	2.67×10^{17}
Bandwidth	0.15%	0.27%	0.41%
Spectral Energy Density (ph/s eV)	5.24×10^{7}	8.47×10^{6}	2.62×10^{6}





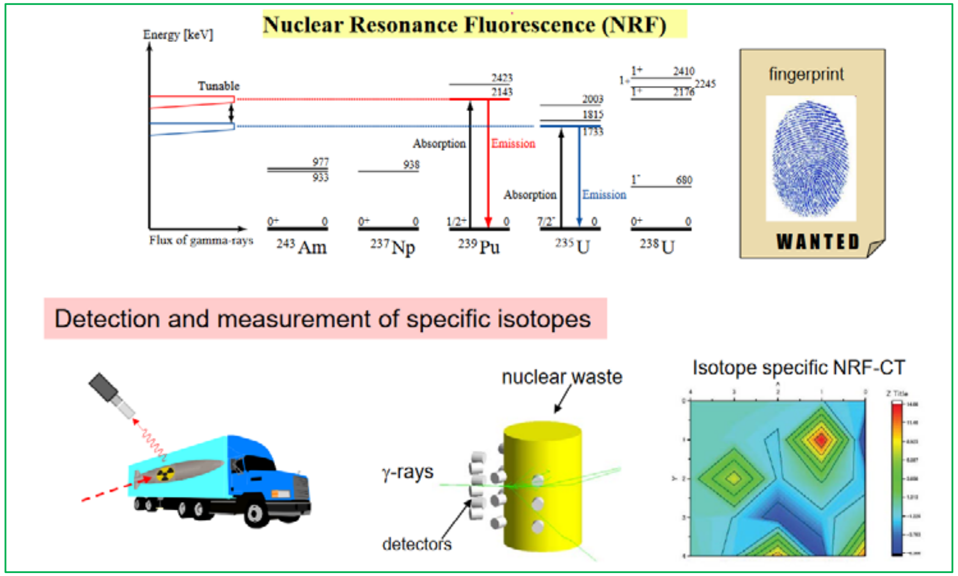
Linac ICS Spectral Parameters			
Parameter	ELI-NP (2014) [62]	FAST (2017) [65]	MEGa-ray (2011) [7]
γ-ray Energy (MeV)	0.2-19.5	≤ 1.2	0.5-2.3
Spectral Energy Density (ph/s eV)	$0.8-4.0\times10^4$	2×10^5	10^6
Bandwidth	$\leq 0.5\%$	0.8%	0.1%
Photons/pulse (ph)	8.3×10^6	1.9×10^7	8.0×10^7
Photons/sec (ph/s)	8.3×10^8	2.85×10^9	9.6×10^9
Peak Brilliance (ph/s mm^2-mrad^2 0.1% bw)	$10^{20}-10^{23}$	1.5×10^{23}	1.5×10^{20}
Storage Ring ICS Spectral Parameters			
Parameter	NewSUBARU (2009) [66] [67]	HiGS (2013) [68]	
γ-ray Energy (MeV)	0.5-73	1-100	
Spectral Energy Density (ph/s eV)	≤ 9.72	$>1\times10^3$	
Bandwidth	1.2-1.6%	0.8 – 10%	
Photons/pulse (ph)	-	-	
Photons/sec (ph/s)	3×10^5-5.8×10^6	$\times10^7-2\times10^{10}$	
Peak Brilliance (ph/s mm^2-mrad^2 0.1% bw)	-	-	

Comparing the resulting properties with other proposed (red) and existing (blue) ICS gamma sources

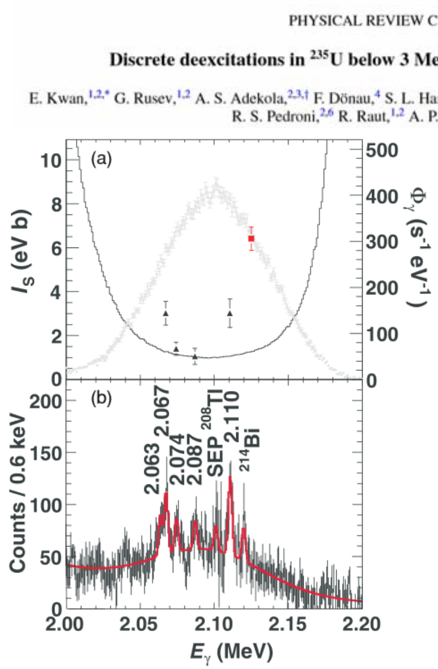
DIANA = 10^4 x existing spectral energy density at HIGS (Duke)
DIANA = 10^3 x proposed ELI-NP (Magurele), 10^2 x proposed FAST (Fermilab)

Nuclear Photonics @ 1 – 3 MeV Gammas: Nuclear Resonance Fluorescence

- At 1 – 3 MeV: (γ,γ′) = NRF, pencil beam of ICS source ideal for Computed Tomography of: e.g. **detection of clandestine nuclear materials**, defects in fuel assemblies (**JAEA** & LLNL studies), assay of spent fuels, unknown legacy wastes, …



Roc Hajima, KEK
ERL-15


PHYSICAL REVIEW C 83, 041601(R) (2011)

Discrete deexcitations in ^{235}U below 3 MeV from nuclear resonance fluorescence

E. Kwan,[1,2,*] G. Rusev,[1,2] A. S. Adekola,[2,3,†] F. Dönau,[4] S. L. Hammond,[2,3] C. R. Howell,[1,2] H. J. Karwowski,[2,3] J. H. Kelley,[2,5] R. S. Pedroni,[2,6] R. Raut,[1,2] A. P. Tonchev,[1,2] and W. Tornow[1,2]


Impact of Monoenergetic Photon Sources on Nonproliferation Applications

Cameron Geddes, Bernhard Ludewigt, John Valentine, Brian Quiter, Marie-Anne Descalle, Glen Warren, Matt Kinlaw, Scott Thompson, David Chichester, Cameron Miller, Sara Pozzi

March 2017

INL
Idaho National Laboratory

- Industrial partner to contribute to feasibility study of ICS driven NRF & photofission in security applications

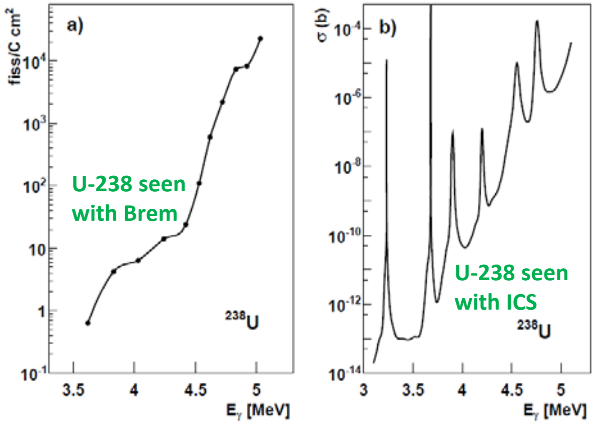
Study on HIγS:
"In addition to the nine previously reported transitions for U-235, 13 more were observed for the first time"

Nuclear Photonics @ 3 - 40 MeV Gammas: Photofission / Transmutation

- At 3 – 40 MeV: (γ,n), (γ,p), (γ,f). The observed broad "dipole resonances" of nuclear structure predicted to actually be composed of **multiple sharp resonances**, storage ring ICS starting to provide evidence.

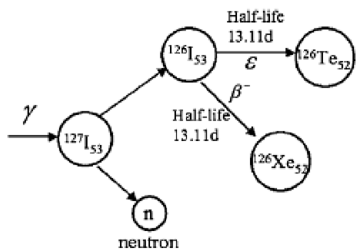
- If we use strong angular collimation and chirping / caustic techniques to hammer down on the bandwidth to < 100 keV = narrower than resonance separations: tune to particular resonance, thereby **choosing the desired decay chain** of a particular isotope – leading to the potential of **selective** isotopic transmutation at industrially relevant quantities **without need for chemical partition**

Predicted "hidden" resonances in photofission cross sections



"Perspectives for photofission studies with highly brilliant, monochromatic γ-ray beams" P. G. Thirolf et. al., EPJ Web of Conferences **38**, 08001 (2012)

Demonstration on NewSUBARU storage ring ICS (2009)




Journal of NUCLEAR SCIENCE and TECHNOLOGY, Vol. 46, No. 8, p. 831–835 (2009)

ARTICLE

Iodine Transmutation through Laser Compton Scattering Gamma Rays

Dazhi LI[1,*], Kazuo IMASAKI[1], Ken HORIKAWA[2], Shuji MIYAMOTO[2], Sho AMANO[2] and Takayasu MOCHIZUKI[2]

[1]Institute for Laser Technology, 2-6 Yamada-oka, Suita-shi, Osaka 565-0871, Japan
[2]LASTI, University of Hyogo, 3-1-2 Koto, Kamigori-marchi, Ako-gun, Hyogo 678-1201, Japan

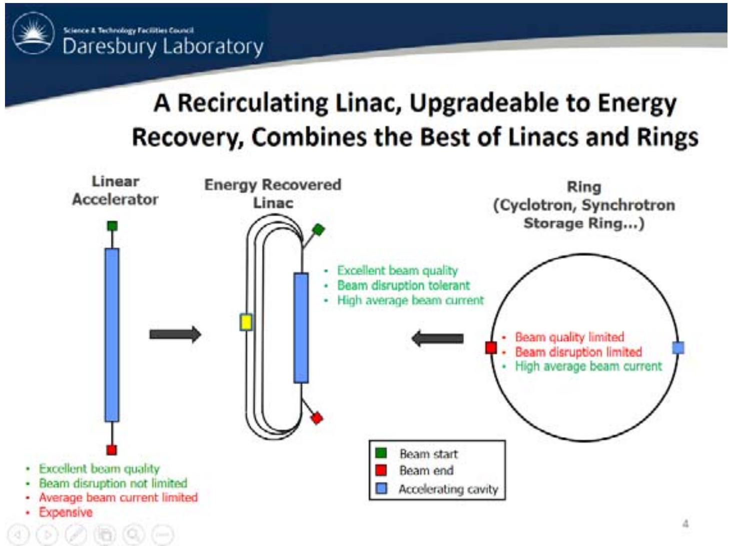
Selective transmutation of the I-127 using ICS (a stand-in stable isotope to prove the principal for problematic I-129 (half-life 16 million years, high chemical activity)

- The dream is to **reduce / change profile,** (even eliminate) burden of **long-lived actinides and fission products** on future waste repositories *(google "into eternity documentary" for the context),* impact public acceptance of waste

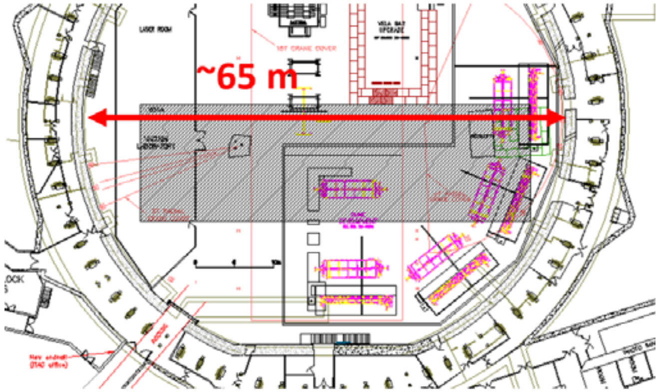
- Additional potential for industrial production of **non-standard medical isotopes** (i.e. not Te-99m) at high specific activity to **enable new treatments**

Why ONLY an ERL will do for these applications?

- **Linac** cannot economically provide high average current for high power FEL / high flux Compton,
- **Storage ring** cannot tolerate large disruption – only perturbations from equilibrium (why storage ring FELs never caught on & why storage ring Compton gamma sources (NewSUBARU / HIGS) have low flux)
- **ERL** can provide high average current & tolerate the ~ few % energy drop / energy spread increase from high power FEL / high flux Compton / internal target



- Propose DIANA to be located in existing Daresbury ex-SRS inner hall
- Estimated capital cost for accelerator < £100M (Gamma and EUV beamlines additional)
- **Builds on the 12+ years of learning on ALICE ERL-FEL @ Daresbury**



Conclusions & Proposed Path

Problem: a UK-XFEL?

- UK has missed the boat for the first wave of XFELs … and the direction of travel is high rep rate and < 1fs sync = **SC** (EU-XFEL upgrade, LCLS-II, SHINE)
- High beam powers (multi-MHz rep rates) enabled by SC technology is the unexplored frontier – e.g. is an X-ray oscillator possible?
- A recirculating linac with energy recovery is the way to make this affordable and extend scientific reach into nuclear domain and high average power industrial FEL applications. **But how to get there? The step change needed from state-of-the-art is risky**

Solution: DIANA

- 1 GeV scale MHz "UK-XFEL test facility" that is **NOT a test facility**! Why is it not a test facility? **Because the motivation for building is at least as compelling as a UK-XFEL itself!**
- High **average power EUV-FEL** and **industrial ICS gamma source** are the killer apps for ERLs! Why:
  - They are **needed** by wider society (problems looking for a solution)
  - An ERL is the **only** way to meet these needs
- **One machine** can satisfy both these, and more besides → confidence that this is the "right" scale / these are the "right" parameters. It is also **one order of magnitude** beyond state-of-the-art in beam power → again the "right" level of stretch / risk. Could also directly be UK-XFEL stage 1
- Proof it's a good idea – others have similar thoughts! **Darmstadt** proposing **DICE** replacement for S-DALINAC – also a separate transport multipass ERL – room for generic design / learning between labs

Acknowledgements

- Special thanks to Dave Douglas (Jefferson Lab) who has worked with myself to develop these ideas

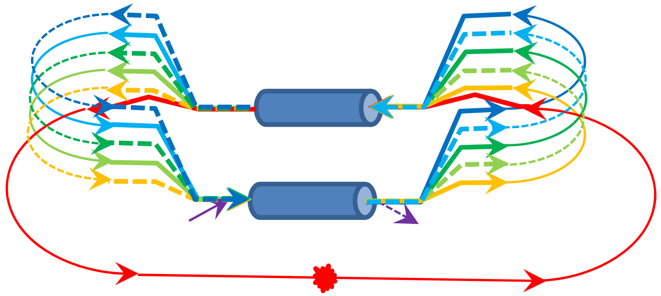
Thanks also:

- Deepa Angal-Kalinin, Alex Brynes, Jim Clarke, Louise Cowie, Dave Dunning, Phillipe Goudket, Frank Jackson, James Jones, Peter McIntosh, Boris Militsyn, Andy Moss, Bruno Muratori, Susan Smith, Mark Surman, Neil Thompson, Alan Wheelhouse (Daresbury Lab)
- Richard York (Facility for Radioactive Ion Beams)
- Steve Benson, Yves Roblin, Todd Satogata, Mike Spata, Chris Tennant (Jefferson Lab)
- Gus Perez-Segurana, Ian Bailey (Lancaster University)
- Tessa Charles (The University of Melbourne / CERN)
- Joe Crone, Hywel Owen (U. Manchester)
- Brian McNeil (U. Strathclyde)

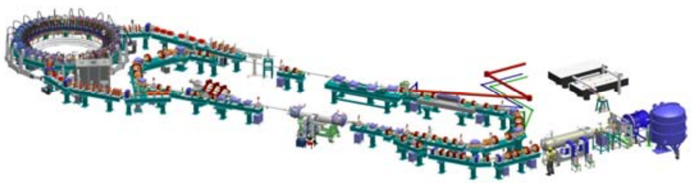
Extra Slides

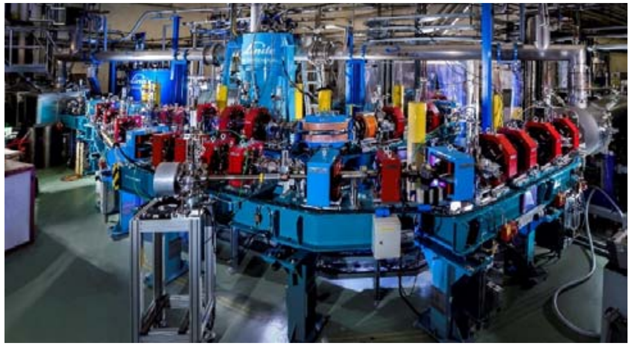
Science & Technology Facilities Council
Daresbury Laboratory

Evolution of ERLs at Daresbury / Cockcroft



… To Industrial Applications



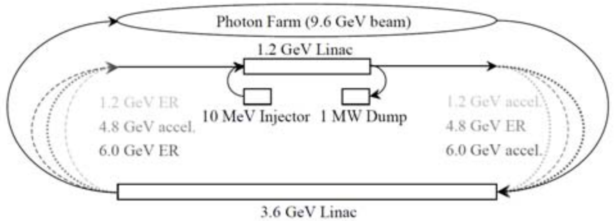


From Accelerator Research …

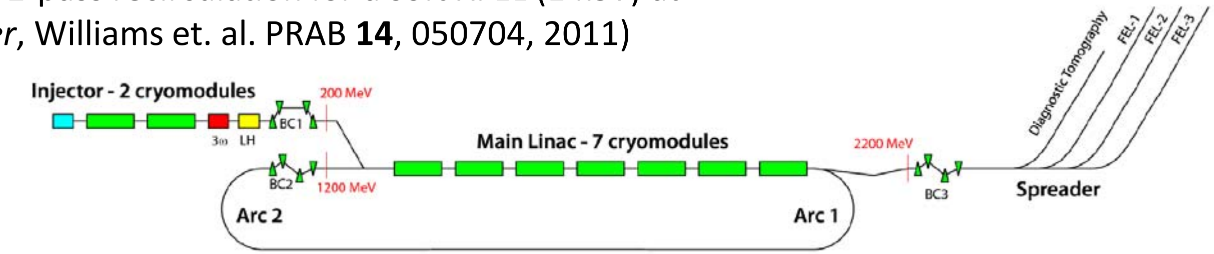
Science & Technology Facilities Council
Daresbury Laboratory

History of Recirculating XFEL Proposals*

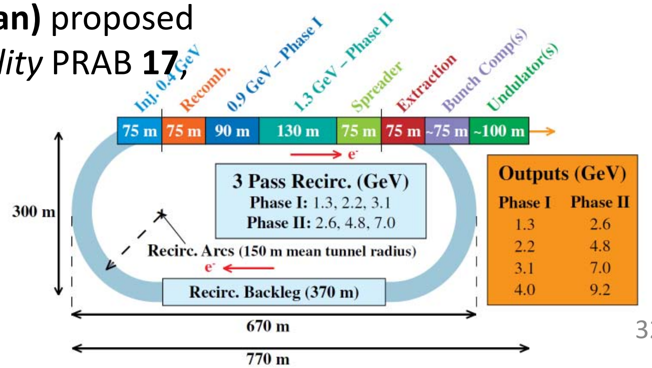
- **2001: GERBAL** considered an FEL among other spontaneous sources (*Generic Energy-Recovering Bisected Asymmetric Linac*, Douglas, ICFA-BD-NL-26, 2001)



- **2010: UK New Light Source** design study considered 2-pass recirculation for a soft XFEL (1 keV) at 1 MHz, (*Recirculating Linac Free-Electron Laser Driver*, Williams et. al. PRAB **14**, 050704, 2011)



- **2014: CEBAF-X** design study to add a soft XFEL to CEBAF lead to **Richard York (Michigan)** proposed 3-pass recirculation for hard XFEL, (*5 keV upgradable to 25 keV free electron laser facility* PRAB **17**, 010705, 2014)



* To my knowledge, all other considerations of recirculation addressed only spontaneous sources or longer wavelength FELs

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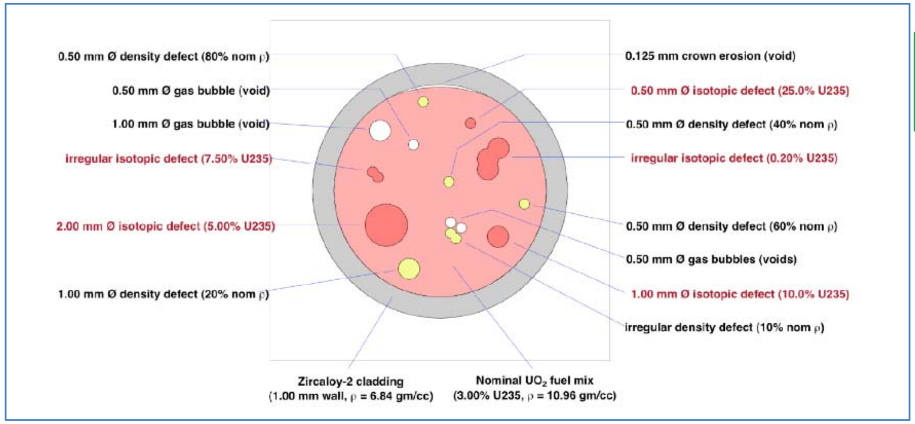
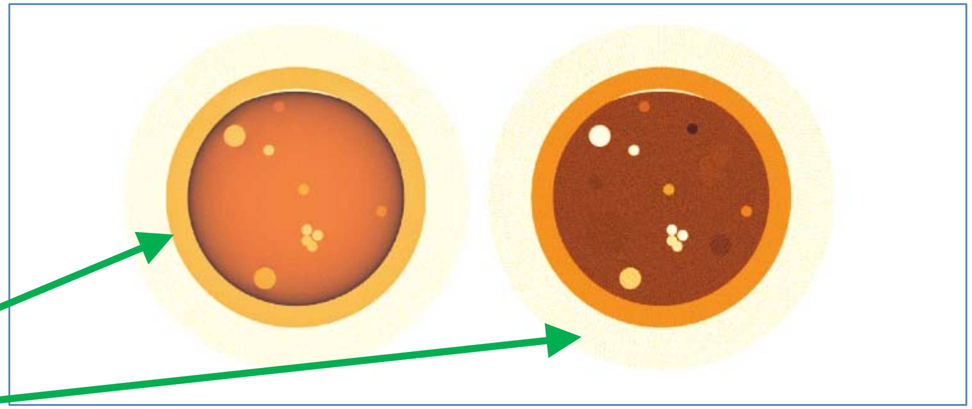
Nuclear Photonics @ 1 – 3 MeV Gammas: Nuclear Resonance Fluorescence

- At 1 – 3 MeV: (γ,γ') = NRF, pencil beam of ICS source ideal for Computed Tomography of: e.g. detection of clandestine nuclear materials, **defects in fuel assemblies** (JAEA & **LLNL** studies), assay of spent fuels, unknown legacy wastes, …



Simulated nuclear fuel rod containing isotopic defects



Simulated resulting image from 2 MeV Brem and 1733 keV ICS shows superior differentiation

NATIONAL NUCLEAR LABORATORY Sellafield Ltd

- Industrial partners to contribute to feasibility study of ICS driven NRF & photofission in nuclear decommissioning applications with **U Manchester Dalton Cumbrian Facility**

Science & Technology Facilities Council
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Possible Radionuclide Generation using a Narrowband Gamma Source

- *"Photonuclear reactions allow the production of higher specific activity and / or more economically than classical methods for* ***Sc-47, Ti-44, Cu-67, Pd-103, Sn-117m, Er-169, Pt-195m, Ac-225****"*

- Again the underlying transitions and their cross sections are not well determined = need for systems capable of producing this data – for example … *"the narrow bandwidth of γ excitation may* ***make use of the fine structure of Pygmy Dipole Resonance leading to increased cross sections****"*

Appl Phys B (2011) 103: 501–519
DOI 10.1007/s00340-010-4278-1

Applied Physics B
Lasers and Optics

Production of medical radioisotopes with high specific activity in photonuclear reactions with γ-beams of high intensity and large brilliance

D. Habs · U. Köster

- **Example 1: (γ, γ') to produce Pt-195m** – Pt used in chemo, labelling with this radiotracer would demonstrate tumour uptake of chemo – but currently specific activity too low (only 0.04 GBq/mg from HFIR, Oak Ridge) = not enough for clinical trials. Using ICS source to drive (γ, γ') could obtain 70 GBq/mg.

- **Example 2: (γ, n) to produce Ac-225** – an alpha emitter = high LET, coupled to cancel cell bioconjugate can target dispersed cancers e.g. leukaemia – but currently only small quantities available (68 GBq/year from Th-229 decay). Using ICS source to drive (γ, n) on Ra-226 target could obtain 200 GBq/week.

- **Example 3: (γ, 2n) to produce Sc-44** – PET tracer that emits 1157 keV coincident with positron – use triple coincidence to determine point of emission rather than line-of-response. Also a "matched pair" with Sc-47 (a therapy isotope). Currently the generator Ti-44 is used = difficult to produce = expensive. Using an ICS source to drive (γ, 2n) on Ti-46 (natural abundance 8%) could obtain 200 MBq of Ti-44, generator can be eluted many times / day for ~10 years.